approach are techniques which limit mechanisms leading to irreversible distortion of the pulse, such as nonlinear frequency generation, frequency dependent gain, and preferential amplification of the pulse leading edge.

We would like to thank specially F. A. Beisser who provided essential technical support.

[1]E. P. Ippen and C. V. Shank, in *Ultrashort Light Pulses*, edited by S. L. Shapiro (Springer, New York, 1977) Chap. 3.
[2]A. Migus, C. V. Shank, E. P. Ippen, and R. L. Fork, IEEE J. Quantum Electron. **QE-18**, 101 (1982).
[3]C. V. Shank, R. L. Fork, B. I. Greene, F. K. Reinhart, and R. A. Logan, Appl. Phys. Lett. **38**, 104 (1981).
[4]C. V. Shank, R. L. Fork, R. F. Leheny, and J. Shah, Phys. Rev. Lett. **42**, 112 (1979).
[5]R. L. Fork, B. I. Greene, and C. V. Shank, Appl. Phys. Lett. **38**, 671 (1981).
[6]C. V. Shank, R. L. Fork, R. Yen, R. H. Stolen, and W. J. Tomlinson, Appl. Phys. Lett. **40**, 761 (1982).
[7]D. M. Bloom, L. F. Mollenauer, C. Lin, D. W. Taylor, and A. M. DelGaudio, Opt. Lett. **4**, 297 (1979).
[8]E. B. Treacy, IEEE J. Quantum Electron. **QE-5**, 454 (1969).
[9]For a discussion of the causes of nonlinear frequency generation see, e.g., D. H. Auston, in *Ultrashort Light Pulses*, edited by S. L. Shapiro (Springer, New York, 1977) Chap. 4.

High-power, single-mode operation of an InGaAsP/InP laser with a grooved transverse junction using gain stabilization

T. R. Chen,[a] U. Koren, K. L. Yu, K. Y. Lau,[b] L. C. Chiu, A. Hasson, S. Margalit, and A. Yariv
California Institute of Technology 116-B1, Pasadena, California 91125

(Received 1 March 1982; accepted for publication 14 May 1982)

The high-power performance of a groove InGaAsP/InP transverse junction laser fabricated on a semi-insulating InP substrate has been investigated. Peak power of over 250 mW/facet for pulsed operation and 11 mW/facet cw are achieved with stable fundamental mode operation and narrow beam width. It is suggested that the single-mode operation is caused by a gain stabilizing mechanism related to the transverse junction injection profiles.

PACS numbers: 42.55.Px

High-power semiconductor lasers will be desirable in many applications. In optical fiber links, as an example, they can increase the distances between repeaters as well as data transmission rates, resulting in higher efficiency and lower system cost. However, in fiber-optic communication, it is essential that the laser operates in a stable single mode. A high-power laser operating in a stable single transverse mode is rather difficult to achieve. Although there have been many publications on high-power, mode-stabilized GaAs/GaAlAs lasers, only a few InGaAsP/InP high-power lasers have been reported.[1,2]

In this letter, a groove transverse junction stripe (GTJS) laser fabricated on semi-insulating (SI) InP is reported. The laser fabrication process involves only a simple, single step liquid phase epitaxial (LPE) growth. This laser can be used for monolithic integration with other semiconductor devices, such as field-effect transistors,[3] and is also suitable for high data rate modulation because of the small parasitic capacitance and high values of I/I_{th} that can be achieved.

In strongly guiding dielectric waveguide lasers which can support several modes, such as the buried heterostructure (BH) or the channelled substrate BH lasers, it is very difficult to obtain fundamental mode operation when the waveguide width is larger than the effective diffusion length. For vertical injection (i.e., the *p-n* junction is parallel to the wide dimension of the waveguide), the spatial hole burning effect[4] creates a dip in the gain profile at the center of the waveguide, which leads to preferred lasing at high order modes. Some discrimination in favor of the fundamental mode may be provided by a very narrow stripe contact located centrally above the waveguide.[5] It is showed here that for a wide (3–5 μm) buried waveguide with a transverse junction stripe (TJS) type of injection (i.e., with a transverse *p-n* junction located near the middle of the waveguide), the gain pro-

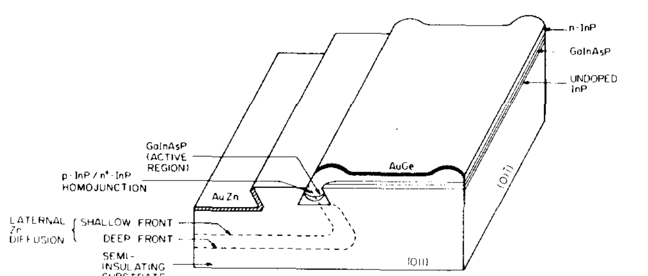

FIG. 1. Schematic representation of the groove transverse junction laser on semi-insulating InP.

[a] Permanent address: Chengdu Institute of Radio Engineering, People's Republic of China.
[b] K. Y. Lau is with Ortel Corporation, Alhambra, CA 91803.

 0003-6951/82/030225-04$01.00

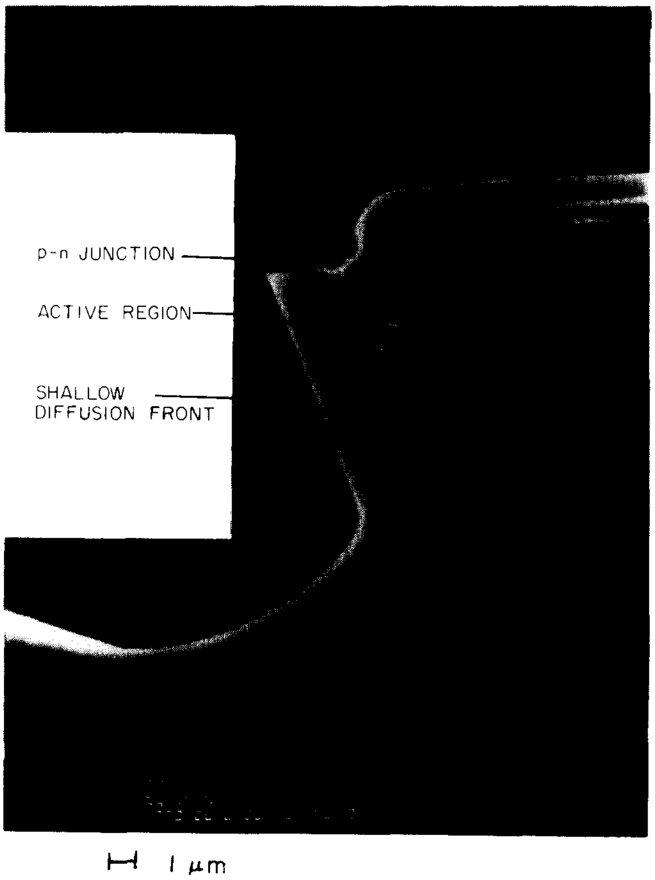

FIG. 2. SEM picture of the transverse junction.

file actually prefers the fundamental mode. This profile provides a stabilizing effect, which is enhanced at high injection and optical power levels. This will be further illustrated.

The laser structure utilized in this work has been reported recently.[3,6] A schematic description of the structure is shown in Fig. 1, and a scanning electron micrography (SEM) photomicrograph is shown in Fig. 2. Three LPE layers: n-InP (undoped, with background electron concentration level at 4–$9\times10^{16}\ \mathrm{cm}^{-3}$), n-InGaAsP (undoped), and n-InP (Sn doped, $2\times10^{18}\ \mathrm{cm}^{-3}$) are grown successively on a grooved and masked SI InP substrate. Then, a Zn diffusion is performed laterally. To achieve high-power operation, the width of the active region is increased to 3–5 μm and the thickness is $\sim$0.5–1 μm at the center of the active region. Also, for stable single-mode operation, the Zn diffusion front is placed somewhere near the middle of the active region. The enlargement of the size of the active region and the location of the transverse junction near its center results in a modest increase in the threshold current compared with that reported previously,[3,6] but vastly improves the transverse mode behavior and output power of the laser.

Since the quaternary active region is completely surrounded by lower index InP, and, in addition, real effective index guiding is attained in the lateral direction by the geometrical structure of the crescent-shaped active region, excellent optical confinement is achieved. As the quaternary layer has a narrower band gap than that of the InP, carrier injection occurs predominantly in the active layer. As a result, relatively low threshold current is obtained. For lasers with $\sim 5\times0.5$–$1\ \mu$m active region and ~ 300-μm cavity length, the threshold current is typically about 40–60 mA, the lowest one attained was 30 mA.

FIG. 3. Current/light-output characteristics under pulse operation. The laser dimension is $5\times0.4\times300$ (in μm).

A typical pulse operation characteristics (light output versus injection current) is shown in Fig. 3. The laser has a threshold current of 50 mA and the lasing wavelength is 1.3 μm. The current pulse employed has a width of 50 ns with a repetition rate of 1 kHz. Output power as high as 260 mW per facet has been achieved (limited by the maximum current obtainable from the pulse generator). Differential quantum efficiency is about 45% for both facets at $P = 60$ mW/facet output power level and decreases gradually as the injection current is increased. This decrease is probably due to increase in the forward bias curent leakage through the InP junction and current heating at high injection levels. Output power at cw operation is 11 mW/facet and is limited by the dc heating as the heat sinking of the laser has not been optimized. The measurement of the temperature dependence of the threshold current showed are T_0 of 70 °K in the room-temperature range.

The far-field patterns of the laser light output at different injection currents are shown in Fig. 4. Stable single fundamental transverse mode operation has been achieved up to the maximum diode drive (45 times threshold current) available from the pulse generator. Measured beam widths (FWHM) are 15° in the lateral direction and $\sim$20° in the vertical direction.

Since the groove lasers are fabricated on semi-insulating substrate with both p and n contacts up, they are very easy to operate in series. Series operation of three to five

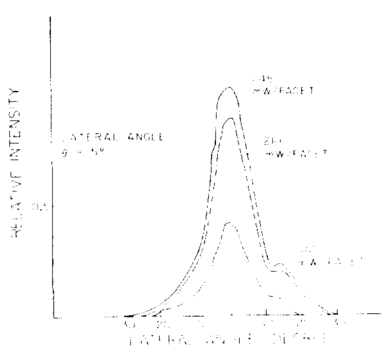

FIG. 4. Far-field pattern: lateral direction at different injection currents.

lasers has been demonstrated, and output power enhancement has been obtained. Series operation of lasers may find applications in systems requiring large output power or signal branching.

In conventional lasers with real index guiding and vertical injection, fundamental lateral mode operation is difficult to maintain at high optical power levels as a result of spatial hole burning. In marked contrast to this, a stabilizing effect takes place in transverse junction injection lasers with real index guiding. As the optical power increases, the gain profile becomes progressively narrower due to the decrease of the stimulated lifetime and thus of the effective carrier diffusion length. If the transverse junction is properly placed near the center of the waveguide, this effect provides stabilization for the fundamental mode, as the following analysis will show.

For simplicity, the real index-guided fundamental mode optical intensity distribution is approximated by

$$P(x) = P(1 - x^2/w^2) \quad |x| < w, \tag{1}$$
$$P(x) = 0 \quad |x| > w,$$

where $\frac{4}{3} wP$ is the total optical power in the mode and $\sqrt{2}w$ is the width (FWHM) of the mode. The carriers are assumed to be injected across the junction which is located at the center of the waveguide, $x = 0$. The steady-state distribution of carriers $n(x)$ on either side of the junction, in the presence of the fundamental mode, is goverend by the diffusion equation with point injection at $x = 0$:

$$\frac{d^2n}{dx^2} = P(x)n(x) + n(x), \tag{2}$$

where x has been normalized by the carrier diffusion length in the material, $n(x)$ and $P(x)$ have been normalized by $1/(A\tau_s)$ and $1/(A\tau_p)$, respectively, where A is the usually defined optical gain constant,[7] τ_s and τ_p are the carrier and photon lifetimes, respectively. Equation (2) is solved in the region $|x| < w$ with the boundary condition $(dn/dx) \times (x = \pm w) = 0$ and $(dn/dx)(x = 0) = I$, where I is the normalized pump current density injected across the transverse junction at $x = 0$. In anticipation that the carriers are almost entirely concentrated near the center of the waveguide under high optical powers, region for solution can be extended to $|x| < \infty$ and the solution to (2) with the optical intensity distribution (1) is given by the parabolic cylinder functions[8]:

$$n(x) = KW(a, \pm bx) \quad x > 0, \tag{3}$$

where

$$a = w\frac{(1+P)}{2\sqrt{P}},$$
$$b = \left(\frac{2\sqrt{P}}{w}\right)^{1/2}, \tag{4}$$

and K is a constant. Here, we have assumed for simplicity a symmetric carrier distribution on both sides of the junction (this is not generally true, as the amount of asymmetry depends on the doping levels, the diffusion constants on both

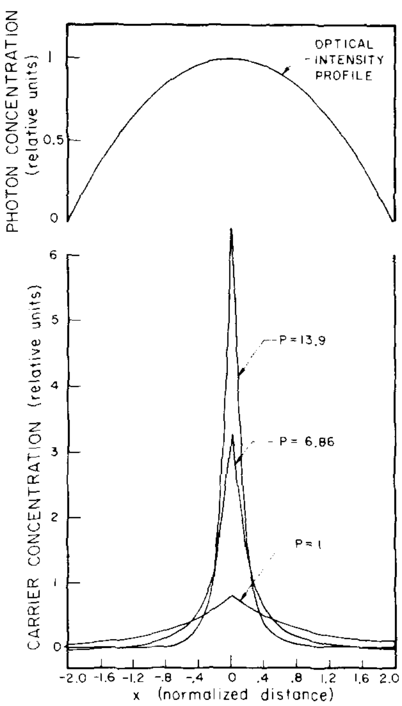

FIG. 5. Calculated carrier concentration for three values of optical power P. The fundamental mode intensity profile assumed in the calculation is also shown.

sides of the junction, and the position of the junction with respect to the optical mode). More exact solutions for this problem will be given elsewhere. The normalization constant K must be chosen so that the total gain in the fundamental lasing mode is constant,

$$\int_{-\infty}^{+\infty} n(x)\,p(x)\,dx = 1. \tag{5}$$

Assuming $w = 2$ (i.e., the fundamental mode width is $2\sqrt{2}$ times the carriers diffusion length). Figure 5 shows the carrier distributions for different optical power levels P ($P = 1$ approximately corresponds to 1.5 mW/facet output power). The localization of the carriers (and thus of the gain) profile at the center discriminates against higher order transverse modes. The gain stabilization effect is enhanced at higher optical powers, thus accounting for the experimental observations described above.

In the above analysis the spatial mode is assumed to be index guided and is independent of the injection level. This is valid up to a certain injection level, as gain guiding may become important at very high level injection and in the case of very wide waveguide. Thus the above analysis is valid when the width of the optical mode guided by the gain profile[9] is much wider than that guided by the real-index waveguide, which is approximately equal to half of the width of the waveguide. When the width of the waveguide is $3\,\mu$m and the diffusion length is assumed to be $2\,\mu$m, it is estimated that index guiding is the dominant mechanism for a peak gain as high as 1000 cm^{-1}, which corresponds to a normalized pump current density I of about 30, and this has been treated as the upper limit of the range of validity in the above analysis.

In conclusion, the high power performance of a groove transverse junction laser fabricated on semi-insulating InP substrate has been investigated. Gain stabilized transverse single-mode operation with narrow beam and high peak power has been obtained.

This work was supported by the Office of Naval Research and the National Science Foundation.

[1]R. J. Nelson, P. D. Wright, P. A. Barnes, R. L. Brown, T. Cella, and R. G. Sobers, Appl. Phys. Lett. **36**, 358 (1980).
[2]Y. Nakano, K. Takahei, Y. Naguchi, Y. Suzuki, H. Nagai, and K. Nawata, Electron. Lett. **17**, 782 (1981).
[3]U. Koren, K. L. Yu, T. R. Chen, N. Bar-Chaim, S. Margalit, and A. Yariv, Appl. Phys. Lett. **40**, 643 (1982).
[4]S. Wang, C. Y. Chen, A. S. Liao, and L. Figueroa, IEEE J. Quantum Electron. **QE-17**, 453 (1981).
[5]G. H. B. Thompson and P. A. Kirkby, Electron. Lett. **15**, 824 (1979).
[6]K. L. Yu, U. Koren. T. R. Chen, P. C. Chen, and A. Yariv, Electron. Lett. **17**, 790 (1981).
[7]H. Kressel and J. K. Butler, *Semiconductor Lasers and Heterojunction LED'S* (Academic, New York, 1977), p. 556.
[8]M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions* (National Bureau of Stands, Washington, D. C., 1972), p. 685.
[9]K. Y. Lau and A. Yariv, J. Appl. Phys. **52**, 641 (1981).

Low threshold, high efficiency $Ga_{1-x}Al_xAs$ single quantum well visible diode lasers grown by metalorganic chemical vapor deposition

R. D. Burnham, D. R. Scifres, and W. Streifer
Xerox Palo Alto Research Centers, Palo Alto, California 94304

(Received 2 April 1982; accepted for publication 26 May 1982)

Laser threshold current density and emission wavelength were investigated for broad area single quantum well double heterostructure (SQWDH) $Ga_{1-x}Al_xAs$ lasers grown by metalorganic chemical vapor deposition (MOCVD) under pulsed operation at room temperature. The shortest lasing emission wavelength was 7065 Å. At that wavelength, the threshold current density was 1 kA/cm^2 for a Fabry–Perot diode of 500-μm cavity length and the external differential quantum efficiency was 48%. These values are significantly better than those previously reported for $Ga_{1-x}Al_xAs$ DH lasers operating under similar conditions at the same wavelengths. We attribute the improved performance in part to the quantum size effect (active layer thickness 400–600 Å).

PACS numbers: 41.44.Px, 81.10.Bk

Visible light emitting semiconductor lasers in the 7000–8000-Å wavelength range have desirable properties for use as sources in office information printing and optical memory systems. Several reports of visible lasers using ternary and quaternary III-V compound materials have appeared, specifically, diodes lasing at wavelengths of 6470 Å in an $In_{1-x}Ga_xP_{1-y}As_y/GaAs_{1-z}P_z$ system (pulsed, 300 K, $J_{th} = 20$ kA/cm^2),[1] 7000 Å in an $In_{1-y}Ga_yP/GaAs_{1-z}P_z$ system (cw, 283 K, $J_{th} = 3.4$ kA/cm^2),[2] 7276 Å in a $Ga_{1-x}Al_xAs/GaAs$ system (cw, 300 K, $J_{th} = 2$–3 kA/cm^2),[3] 7140 Å in a $Ga_{1-x}Al_xAs/GaAs$ system (channeled substrate planar (CSP) structure, cw, 300 K, $J_{th} = 7.5$ kA/cm^2),[4] and 7100 Å in a $Ga_{1-x}Al_xAs/GaAs$ system (terraced substrate TS structure cw, 300 K, $J_{th} = 7$ kA/cm^2).[5]

Here we report on quantum well heterostructure (QWH) lasers, which have some performance features which may make them superior to that of double heterostructure devices. (See Holonyak *et al*[6] for a review of QWH lasers.) In particular for QWH lasers, the density of states function is altered from a parabolic continuum to steplike discrete levels. It appears that the temperature dependence of laser threshold is thus reduced. Bandfilling and recombination are also possible over a very large energy range (as high as ~ 300 meV).

These attributes may allow improved performance such that QWH lasers play an ever increasing role in injection laser technology, especially in the visible portion of the spectrum.

Previously, several examples of QWH lasers which emit in the visible portion of the spectrum at room temperature have been reported. These experiments were done with photopumped crystals rather than with an electrically pumped device. We note 6550-Å pulsed operation in an $In_{1-x}Ga_xP_{1-z}As_z$ crystal grown by liquid phase epitaxy (LPE),[7] 6785-Å pulsed output in $Ga_{1-x}Al_xAs$ grown by metalorganic chemical vapor deposition (MOCVD)[8] and 7270-Å cw operation in the $Ga_{1-x}Al_xAs$ system grown by molecular beam epitaxy (MBE).[9]

In this letter, we report $Ga_{1-x}Al_xAs$ MOCVD-grown single quantum well double heterostructure (SQWDH) laser operation in the visible portion of the spectrum with electri-

 0003-6951/82/030228-03$01.00